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A GENERAL PURPOSE DIGITAL SYSTEM FOR ON-LINE CONTROL OF AIRBREATHING PROPULSION SYSTEMS

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16. Abstract

A digital system to facilitate development of airbreathing propulsion system controls is described from an operational and design viewpoint. The system is portable and capable of real-time on-line operation in the range of dynamics normally encountered in airbreathing propulsion systems.

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A GENERAL PURPOSE DIGITAL SYSTEM FOR ON-LINE CONTROL OF AIRBREATHING PROPULSION SYSTEMS

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SUMMARY

Control development for advanced airbreathing propulsion systems is being greatly simplified through the use of electronic, general purpose computers. Digital computers are particularly well suited to the complex scheduling and logical manipulations necessary in the control of complex propulsion systems. Control concepts may be easily implemented and checked without hardware development. A digital control system developed for this purpose is described herein from an operational and design viewpoint.

The heart of the system is a 750-nanosecond-cycle-time, 16-bit-word digital computer with 16 384 words of memory. Interface units provide for inputting both analog and periodic signals and outputting both analog and logical commands. A signal processing unit is incorporated for signal conditioning, isolation, and monitoring, as well as for system calibration.

INTRODUCTION

As aircraft requirements advance to higher Mach numbers, larger payloads, and higher efficiencies, the control requirements of airbreathing propulsion systems become more stringent and complex. Engines and inlets need to function together at peak efficiency from subsonic through high-Mach-number operation. Controls must maintain satisfactory propulsion system operation during aircraft maneuvers (e.g., changes in angle of attack), as well as in the presence of unanticipated disturbances such as wind gusts or shock waves from passing aircraft.

Typical manipulated parameters in an airbreathing propulsion system are main burner fuel flow, afterburner fuel flow, exhaust nozzle area, compressor variable geometry, inlet bleed area, and inlet centerbody position. Efficient operation necessitates scheduling these parameters as multivariable functions of other aircraft parameters.

For example, engine-fuel-flow scheduling could well be a function of inlet operation and airframe and mission requirements, as well as of such engine parameters as rotor speed and compressor discharge pressure.

A number of methods are available for the implementation of interactive propulsion control systems. Hydromechanical systems are used extensively but, for the most part, provide only minimal interactive capability. Extending this method of implementation to meet modern-day requirements is feasible but offers distinct disadvantages. The computing capability necessary to satisfy these requirements leads to large, heavy hydromechanical systems. The use of three-dimensional cams to generate complex functions requires expensive fabrication and prohibits field adjustment of the control to meet special operational requirements. In addition, adapting a hydromechanical system to function in conjunction with an overall aircraft control system leads to complex instrumentation problems.

Other means of control implementation are being considered to meet modern-day requirements without the disadvantages of hydromechanical systems. Fluidics offers the advantage of light weight and compact size but suffers from a versatility and reliability standpoint. Electronic control is the most promising area of consideration.

Technology developed in the missile and space effort provides the means for fabricating lightweight, reliable electronic systems for airbreathing propulsion system control. In the field of digital electronics particularly, vast computation capability exists in small low-cost packages. Complex scheduling and decision making is easily accomplished through digital computation. Control functions are easily modified, and maintenance and repair become simple tasks. Location of the control is not critical. A complete propulsion control system may be located in the environment of the airframe with signals supplied via electrical transducers and trunked to the control over environmentally tolerant cabling.

Dynamic compensation could be necessary to provide disturbance regulation and setpoint control. The present generation of digital computers with cycle times of the order of 1 microsecond offer real-time calculation capability in the range of dynamics normally encountered in airbreathing propulsion systems.

In addition to its advantages as a propulsion system control technique in an operational flight environment, digital computation is also valuable as a development tool in the formulation and evaluation of new control concepts. General purpose digital computers offer rapid implementation of control concepts, as well as quick, easy modification of these concepts. Evaluation of these concepts is best done on the actual propulsion system. Real-time interfacing of the computer to the propulsion system is therefore necessary. A digital control system designed to facilitate development of engine fuel controls is described in reference 1.

In light of the advantages of digital computations from a development and implemen-

tation standpoint, a general prupose digital control system was developed at Lewis. It is designed to permit real-time, on-line implementation of controls for various configurations of advanced airbreathing propulsion systems. This report describes this control system from an operational and design viewpoint and, in particular, illustrates the hardware features necessary to provide a versatile, general purpose digital control system.

DIGITAL CONTROL SYSTEM DESIGN CONSIDERATIONS

The digital control system was designed to provide versatile, general purpose control of airbreathing propulsion systems: including inlet control, such as shock position regulation and restart scheduling; engine control to provide thrust and specific-fuel-consumption optimization under operational restrictions; and combined inlet-engine interaction optimization.

The prime considerations in the design of the control system are overall signal processing speed and computational size. The system must be capable of accepting the necessary inputs, processing them, and outputting the commands within the frequency range of the propulsion system dynamics. In general, inlet control requires a high frequency of command updates but relatively few measurements and calculations. On the other hand, engine control does not generally require a high frequency of command updates but could entail the measurement of many engine parameters and require massive computation.

System processing speed is a function of computer calculation speed and the versatility of the input/output structure. Calculation speed is maximized through the use of an efficient programming language and a short-response-time computer. Computer response time is denoted by memory cycle time. This is the time it takes to read and re-store a word in memory. Typical cycle times of real-time computers presently available range from a fraction of a microsecond to a few microseconds. Programming languages become less efficient as they are removed from the basic machine language. The most efficient language offers a one-to-one correspondence with machine language. This language is generally called assembly language. The versatility of the assembly instruction set is of prime importance in the selection of a control computer.

Computer response time is further enhanced if some of the mundane computations can be done external to the digital computer. For this reason the system was designed to contain some external computational elements: interval timers for computer computational sequencing, period counters to determine the period of an incoming frequency signal, and elements which indicate that digitalized data are ready for transfer into memory and when the transfer is completed.

The input/output structure should be such as to tie up a minimum of machine calculation time. The normal transfer, of a single word per machine instruction, is not desirable. Direct automatic transfer of blocks of data to and from computer memory and mainframe is necessary.

Portability is another requirement of the system. Control development is best done on comprehensive simulations of the propulsion system. Therefore, easy, reliable movement of the control system between the simulation laboratory and various test facilities is necessary. Two alternatives to portability were considered: central location of the system with longline communication to the various facilities, and van mounting of the system. Both alternatives were rejected on the basis of cost and user's convenience.

Other design considerations, as well as operational descriptions of the various units making up the digital control system, are given in the following sections.

GENERAL SYSTEM DESCRIPTION

The digital control system is made up of several distinct units:

(1) A digital computer designed for real-time control applications

(2) A digital interface capable of converting both analog and frequency signals to computer-compatible digital words and converting computer generated words to analog and logical outputs

(3) Programming peripherals consisting of a high-speed, paper-tape reader and punch and a teletype

(4) A signal processing unit (SPU) which provides signal conditioning and monitoring as well as some analog computation capability between the digital interface and the propulsion system to be controlled

The digital computer, digital interface, and programming peripherals were supplied as a system from a digital computer manufacturer. The signal processing unit was assembled at Lewis from purchased components.

The system, excluding the teletype, is housed in five distinct racks (see fig. 1) requiring approximately 11 running feet of floor space. Intercabinet cabling is accomplished in the rear and allows a maximum of 10 feet of spacing between adjacent cabinets. The system was designed to be portable. Typical teardown and setup time is 1 day, and complete system checkout requires 1 week.

The block diagram of figure 2 illustrates the basic units and interconnection of the digital control system. All signals, to and from the propulsion system, pass through the signal processing unit. This unit provides input signal isolation, calibration, signal processing (dynamic filtering and analog computer calculation), and signal monitoring. The system will accept high-level (±10 V range) analog signals from standard pressure

transducers or thermocouples and frequency signals direct from flowmeters and magnetic rotor speed transducers. System outputs may be directed to electrohydraulic servosystems of the type described in reference 2.

The digital interface consists of a high-level, analog signal acquisition unit; a frequency signal acquisition unit; an analog signal output unit; a logical output unit; and an external priority interrupt processor. The digital interface communicates with the computer on either a single-word or a block-data-transfer basis. The programming peripherals communicate only by single-character transfer. The signal handling capability of the system is given in table I.

DIGITAL COMPUTER DESCRIPTION

The computer has 16 384 words of memory. Each word consists of 16 binary bits. All bits are interrogated in parallel with a read - re-store memory cycle time of 750 nanoseconds. The computer consists of four major units: memory, control, arithmetic, and input/output (ref. 3).

Memory Unit

The memory unit stores instruction words which define computer operation and data words upon which the computer operates. Memory is divided into 32 groups called maps. Instructions may directly reference memory data only in the map in which the instruction is contained. Intermap reference to memory data must be made indirectly at the cost of one additional memory cycle and one extra memory location (to hold the memory address).

Control Unit

The control unit sequentially interrogates instruction words and issues commands to operate the computer. This unit allows infinite-level indirect addressing and total core indexing.

Arithmetic Unit

The arithmetic unit performs computation as directed by the control unit upon

memory data words and data words supplied by the input/output unit. Hardware multiply-and-divide is contained in this unit, as well as an independent index register. Arithmetic operations utilize two's complement binary arithmetic with negative numbers stored in two's complement form.

Input/Output Unit

The input/output unit transmits data words, commands, and status reports between the computer and the digital interface, and programming peripherals. Data transfer may be made directly to, or from, memory or to the arithmetic unit. In addition to the normal single-word input/output, three-block data transfer units are utilized. Two of these units are tied to the analog acquisition unit of the digital interface. One unit, upon initialization, automatically transfers channel commands to the multiplexer, while the other transfers digitalized data into memory. Automatic input of digitalized analog signals is thus accomplished. The third-block data transfer unit is available for general purpose data transfer. Block data transfer is made on a cycle stealing basis, interrupting normal computer operation for only 1 cycle (750 nsec) per word transferred. The maximum transfer rate is 666 500 words per second.

Miscellaneous Features

The computer utilizes a hardware-priority interrupt structure to enhance its communication capability with other computational elements in the control system, and to alleviate itself from having to continuously check for random, but important, events occurring in the propulsion system. The computer has 28 individual levels of priority interrupts of which 18 are tied to other system computational elements and 10 are available for monitoring propulsion system events through the priority interrupt processor. Each data acquisition unit in the digital interface informs the computer of the completion of the digitalizing process through a priority interrupt signal. Time intervals are indicated to the computer through priority interrupts from the interval timers. Random events occurring in the propulsion system are determined in the priority interrupt processor and communicated to the computer through a priority interrupt. These computational units and their operation are discussed more thoroughly in the following paragraphs.

Upon receiving a priority interrupt the computer stops its normal calculation and processes a special routine assigned to that interrupt. When this routine is completed, the computer resumes its normal calculation. Each interrupt is assigned a certain

priority level; that is, some interrupts are more important than others. The computer processes each interrupt in the order of their priorities. A lower-order priority interrupt may be interrupted by a higher-order interrupt, but not conversely. Each level may be selectively enabled and disabled under program control, except for two special interrupts. These are the power fail-safe and stall alarm interrupts. Power failure will initiate a power fail-safe interrupt before the computer becomes completely inoperative (at 80 V ac). This interrupt will allow execution of 30 memory cycles of computation in which the control system may be put into a fail-safe mode. The stall alarm prevents the computer from "hanging up." If the program counter has not advanced in 32 machine cycles, this interrupt is triggered and suitable action may be taken in the processing routine assigned to this level.

A 60-hertz clock incorporated in the computer main frame gives a priority interrupt every 1/60 of a second. This unit provides a means of tabulating events with run time. In addition, two interval timers are incorporated in the system. A 16-bit word is transferred to a timer from the computer. The word is then counted down to zero at one of 10 selectable rates ranging from 10 to 572 kilohertz (see appendix). At zero, the timer initiates a priority interrupt. In this manner, time-dependent control functions may be generated.

DIGITAL INTERFACE

The digital interface consists of five subunits: analog acquisition, frequency acquisition, analog output, logic output, and priority interrupt processor. A brief description of the operation of each subunit follows, with complete specifications given in the appendix.

Analog Acquisition Unit

Figure 3 illustrates the configuration of the analog acquisition unit. The multiplexer will accept 64 channels of high-level (±10 V) signals from the signal processing unit. When a channel command is received from the computer, the appropriate channel is presented to the sample-and-hold amplifier. This amplifier holds the voltage until the digitalizing process is complete. The maximum digitalizing rate is 20 000 words per second. The digital word is comprised of 12 binary bits (plus sign) in computer compatible format. This word is transferred into the most significant 13 bits of the computer word. The digitized word format in octal notation is given in table II. Note that the ±10-volt, full-scale values are set below the full-range value. This allows detection of an overscale voltage prior to overflow.

Frequency Acquisition Unit

Figure 4 illustrates the configuration of the frequency acquisition unit. The purpose of this unit is to convert periodic signals into digital words compatible with the computer. This allows direct measurement of engine fuel flows and rotor speeds. Ten channels of period-to-digital conversion are available in the interface with possible expansion to 20 channels. Each channel will accept signals in the range of 100 millivolts to 30 volts peak to peak. Either continuously varying (e.g., sinusoidal) or pulsatile signal measurement is possible.

Pulsatile signals representative of engine rotor speed are obtained from magnetic pickup devices operating with a specially selected gearwheel. This gearwheel device is normally driven at some reduced rotational speed off the engine's mechanical power takeoff. The number of gear teeth is selected to provide a frequency compatible with the measurement resolution desired. For example, proper component selection would allow a 20 000-rpm engine shaft speed to be monitored with a 1-kilohertz pulsatile signal. The period conversion unit would be capable of detecting a 1-hertz, or 20-rpm, change in engine speed with the accuracy given in table III.

Each unit is independently capable of providing a digital period representation every one or four periods of the incoming signal (switch selectable). The four-period option allows period averaging over one complete revolution of a four-bladed turbine flowmeter. Measurement distortion may be eliminated in this manner, sacrificing the rate of information updating.

The unit was designed to operate over a frequency range of 20 hertz to 1 kilohertz. Four switch selectable clock rates are available, providing accuracies as given in table III. In addition, an external clock source may be used to provide desired accuracies over abnormal frequency ranges.

Referring to figure 4, input signals are applied to a zero detector (saturable amplifier) which issues a square-wave output that is dependent on the polarity of the signal. The zero detector gates a selected clock rate into a binary counter on the first positive crossing of the input signal. At the second positive crossing, the contents of the counter are transferred to the output buffer register, the counter is cleared, and the clock rate is again gated into the counter. Four-period averaging modifies the operation accordingly. Upon update of the buffer register, a priority interrupt is issued to the computer, indicating a data-ready condition.

The output word consists of 16 bits. Twelve bits contain the period information, three bits denote the selected clock rate, and one bit indicates a one- or four-period count.

Analog Output Unit

Figure 5 illustrates a typical channel of the analog output unit. The unit consists of 26 channels of digital-to-analog conversion, each independently addressable by the computer. A converter receives a digital word and converts it into a current level through a ladder network. An analog signal is then derived at the output of the operational amplifier. Each operational amplifier will hold its output until a new digital value is received in the buffer register from the computer. Data sampling skew is a function of computer transfer rate alone.

Of the 26 channels, 16 have 11-bit-plus sign resolution and 10 have 12-bit-plus sign resolution. The word formats are similar to that of the analog acquisition unit (table II), maintaining the scaling necessary to operate on system inputs. The analog voltage output range is from -10 to +10 volts with an accuracy of ±1 least-significant bit. The output is capable of stably driving a 10-kilohm load through 50 feet of line. Each channel has a minimum slew rate of 1 volt per microsecond and a settling time of 20 microseconds to within 0.05 percent of the final value for a step of 0 to 10 volts.

Logical Output Unit

Figure 6 illustrates the configuration and pertinent circuitry of the logical output unit. This unit consists of 64 channels. Four digital buffer registers are assigned to this unit, each independently addressable and each corresponding to a 16-bit digital word. Each bit sets the output of a particular logic channel. Of the 64 logic channels, 32 are electronic switches and 32 are contact closures.

A "one" in a selected bit causes the electronic switch associated with this bit to conduct. An external voltage applied to this switch is thus grounded. Each switch is capable of handling voltages to 30 volts and currents to 100 milliamperes.

A "one" in a bit associated with a contact closure acts through an electronic switch to short two externally applied signals together. Maximum ratings for the contact closures are 24 volts dc at 100 milliamperes.

Priority Interrupt Processor

The priority interrupt processor contains 10 channels. A typical channel is illustrated in figure 7. Each channel consists of a comparator and an edge-to-pulse converter (monostable multivibrator).

These units are used to trigger the computer priority interrupts, as illustrated in

figure 2. The comparator output may be used to provide a continuous priority interrupt to the computer as long as a particular condition exists. The comparator output may also be used to drive the edge-to-pulse converter. The converter output will initiate a momentary priority interrupt for a high comparator output.

Comparator action on two varying signals or on a single signal against an internal reference is possible. The comparator may be switched to initiate an interrupt on either an increasing or decreasing signal of either positive or negative polarity.

SIGNAL PROCESSING UNIT

As indicated earlier, the SPU was assembled in-house at Lewis. It was designed to interfacc the purchased digital system to the propulsion controls experimental hardware. It also includes features intended to increase flexibility in the calibration and operation of the control system. In particular, the SPU provides

(1) Ground isolation between the facility and the control unit

(2) Signal filtering

(3) Analog computation for propulsion system simulation or generation of time-dependent control functions

(4) Flexibility in signal routing between the facility and the control unit

(5) Calibration of the system

(6) Comparators and signal conditioners for use with priority interrupts

(7) Signal monitoring

As illustrated in figure 8, the SPU is made up of a number of subunits. These units are housed in a double relay rack. The subunits are instrumentation amplifiers, status and control panel, filter unit, calibration unit, multiplexer input switching unit, patch system, reference supply, digitally programmable voltage source, counter, digital voltmeter, and analog computer.

With the exception of the frequency signals, all signals within the SPU are single ended and shielded. Double-ended signals, transmitted from the propulsion system, are converted to single-ended signals through the use of isolation amplifiers. Outputs from the SPU are double ended and terminated in isolation amplifiers at the propulsion system, providing complete ground isolation of the control system from the propulsion system. High-quality analog ground is carried throughout the SPU and into the digital interface. Cabinet grounds are kept separate from analog ground and used to minimize computer generated radiofrequency noise. Digital ground within the computer and digital interface is also distinct from analog ground but tied to this ground at a single point.

As shown in the block diagram of figure 9, all connections between the propulsion system and the SPU are made through a connection panel in the rear. The panel will

accommodate 100 double-ended shielded inputs from the propulsion system and 54 single-ended shielded outputs to the propulsion system. The outputs are wired directly to the SPU patch panel; the inputs are wired to the calibration unit.

Calibration Unit

The calibration unit consists of a bank of 100 double-pole, double-throw relay contacts. The signal inputs are connected to the normally closed side of these contacts and calibration signals are connected to the normally open side. Sixteen pairs of contacts are devoted to frequency signals, with the corresponding calibration signals being derived from four fixed-frequency oscillators (20, 100, 500, and 1000 hz). These oscillators are switch selectable on the SPU control panel. Eighty-four pairs of contacts are devoted to analog signals, with calibration derived from the programmable voltage source. Failure of any relays in this unit may be detected by the computer through the use of an available priority interrupt. This interrupt is generated any time any relay in the unit is in the "calibrate" mode.

Isolation Amplifiers

The analog signals are wired directly from the calibrate unit to isolation amplifiers. Eighty-four such amplifiers are provided. These amplifiers operate with unity gain and a typical input impedance of 50 megohms. The amplifiers provide isolation of the inputs from the propulsion system and provide single-ended outputs. These outputs terminate at the patch panel.

Filter Unit

Twenty-four plug-in-type dynamic filters are available at the patch panel. These are fourth-order Butterworth filters. Break frequencies are selected to suit the control problem. Standard values of 20, 100, and 200 hertz are available.

Patch Panel

Frequency signals pass directly from the calibration unit to the patch panel for signal monitoring purposes. These signals are then patched to the input of the frequency

acquisition unit. Also terminated at the patch panel are the inputs to the analog acquisition unit, the inputs to the priority interrupt processor, and the outputs of the analog output unit.

Multiplexer Switching Unit

The multiplexer switching unit is used to manually or automatically (under computer supervision) switch the inputs of the multiplexer from a "test" position to a "run" position. Its inputs and outputs are available at the patch panel. The unit consists of 64 channels of double-pole, double-throw relay contacts (shields are also switched). The occurrence of a "test" mode in any group may be sensed by the computer through a priority interrupt output of the unit.

Using this unit and paralleling the outputs of the analog output unit, controls may be exercised on a simulation of the propulsion system for checkout. Then, without disturbing the patch-panel wiring, the control system may be switched to the control of the actual propulsion system.

Analog Computer

A small analog computer is housed in the SPU. Its complement is given in table IV. Thirty trunk lines link the computer to the patch panel. This unit is available for simplified plant simulation or to provide limited control dynamics and thus hybrid control capability.

The analog computer swings out of the SPU, and programming is done in the rear. Amplifier balancing and general trouble shooting are done on the front panel.

Control Panel

The SPU control panel is shown in figure 10. This unit provides mode control of the calibration unit, the multiplexer switching unit, and the analog computer. Automatic control of these units may also be selected on the control panel. In this case the digital computer acts through the contact closure outputs of the logical output unit to specify (1) the "calibrate-operate" mode of the calibration unit, (2) the "run-test mode" of the multiplexer switching unit, and (3) potentiometer-set, reset, hold, and operate modes for the analog computer. Contact closures are also used to specify the voltage output of the programmable voltage supply.

The control panel also allows display of the status of electronic switches in the logical output unit. These switches not only provide program status information but also drive single-pole, double-throw relays for generation of discrete control functions (e.g., solenoid valves).

A readout system is available on the control panel which allows digital voltmeter or scope monitoring of virtually all signals at the patch panel, all amplifiers and potentiometers on the analog computer, and all power supplies in the SPU. Selection of as many as 500 signals is possible. Automatic display of analog computer overloads is also present on the control panel.

Option switches are available on the control panel primarily for changing digital computer program modes. These switches may be tied to priority interrupt channels to initiate the program changes.

PROGRAMMING PERIPHERALS

The computer is programmed through the use of paper tape. The system includes a high-speed, paper-tape reader and punch. The reader operates at 300 characters per second - one character consists of eight binary bits. Sensing is accomplished through the use of photocells. The punch operates at a rate of 110 characters per second using a sprocket drive.

Paper tapes may be generated on a ASR 35 teletype and may also be read into the computer by this unit. The teletype is also the only method of data recording available in the digital control system.

SOFTWARE

Two basic types of program preparation systems are provided: a symbolic Macro assembler and a full FORTRAN IV compiler. Programming may be done in one or the other, or in any arbitrary mixture of the two systems. Compiling is a one-pass procedure, while assembly require two passes. An update program is available for easy update of programs written in either language.

A comprehensive library package allows computation of single-precision floating point, double-precision floating point, and complex floating point functions.

Maintenance routines provide automatic checkout of the computer, the digital interface, the signal processing unit, and the programming peripherals.

CONCLUDING REMARKS

The digital system described herein will provide a versatile tool in the development of controls for airbreathing propulsion systems. The speed, accuracy and complement of the system is sufficient for real-time implementation of setpoint and regulatory controls for inlets and engines, and for combined inlet and engine configurations. The system is portable and may easily be set up in various test facilities. Automatic calibration checks and software diagnostics of hardware failures alleviate most setup problems. The system has proved to be a useful and reliable tool in control applications.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 7, 1970,
720-03.

APPENDIX - SYSTEM SPECIFICATIONS

Digital computer	
Magnetic core memory size, words	16 384
Word length, bits plus parity	16
Memory cycle time, nsec	750
Add time, μsec	1.5
Subtract time, μsec	1.5
Multiply time, μsec	4.5
Divide time, μsec	8.25
Load time, μsec	1.5
Store time, μsec	1.5
Indirect addressing	Infinite
Indexing	Total memory
Priority interrupts	28 Separate levels
Index registers:	
Independent	1
In conjunction with lower accumulator	1
Physical size, in.:	
Width	24
Height	62
Depth	30
Interval timers	
Complement	2
Accuracy, clock pulses	±1
Clock rates, kHz	572, 286, 160, 143, 80, 71.5, 40, 35.75, 20, 10
Counter	16-Bit binary
Output	Priority interrupt to computer
Analog acquisition unit	
Overall sample rate (maximum), kHz	20
Resolution of digital data, bits	12 (plus sign)
Output code	Two's complement
Number of channels	64
Input range, V full scale	±10
Input impedance, MΩ (shunted by 10 pF)	10
Maximum source resistance, Ω	1000
Conversion time, μsec	38
Input settling time, μsec	9
Sample-and-hold aperture time, nsec	500
Safe input voltages, V	±20 sustained ±100 for less than 100 μsec
Total error with calibration, percent	0.073

Frequency acquisition unit	
Number of channels	10
Nature of input	Continuously varying or pulsatile
Resolution of digital data, bits	12
Switch selectable clock rates, kHz	20, 80, 100, 400, external
Overall accuracy, bits	±1
Update rate	Once per cycle of input frequency
Maximum input frequency, kHz	1
Input amplitude range	100 mV to 30 V peak to peak
Analog output unit	
Total number of digital-to-analog conversion channels	26
Resolution (10 channels), bits	12 (plus sign)
Resolution (16 channels), bits	11 (plus sign)
Output voltage range, V full scale	±10
Output current (maximum), mA	10
Output impedance, Ω	<1
Accuracy (12 bit), percent of full scale	±0.1
Accuracy (13 bit), percent of full scale	±0.05
Slew rate, V/μsec	1
Settling time for 10-V step to within 0.05 percent of final value, μsec	20
Logical output unit	
Number of electronic switch outputs	32
Number of contact closure outputs	32
Maximum voltage, V	30
Maximum current, mA	100
Priority interrupt processor	
Number of channels	10
Input impedance, kΩ	47
Input voltage range, V	±10
Comparator switching	Trigger on rise or fall
Comparator hystersis	Adjustable from 35 mV to 650 mV
Comparator output, V	+7
Monostable multivibrator:	
Pulse width, μsec	3
Pulse height, V	+7

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TABLE I. - SIGNAL PROCESSING CAPABILITY

	Present complement	Fully expanded
Signal inputs from propulsion system	100	100
Signal outputs to propulsion system	54	54
Analog-to-digital conversion channels	64	64
Period-to-digital conversion channels	10	20
Logical outputs	64	64
Digital-to-analog conversion channels	26	42
External priority interrupt	10	22

TABLE II. - ANALOG-TO-DIGITAL WORD FORMAT

7777_8	+ Full range
7640_8	+ Full scale (+10 V)
0000_8	Zero (0 V)
10140_8	- Full scale (-10 V)
10000_8	- Full range

TABLE III. - FREQUENCY ACQUISITION UNIT ACCURACY

Frequency range, Hz	Worst accuracy over the range, percent	Clock rate, kHz
20 to 500	±0.625	20
100 to 500	±0.125	80
20 to 1000	±1.25	100
100 to 1000	±0.25	400

TABLE IV. - ANALOG COMPUTER COMPLEMENT

Amplifiers (total)	38
Integrator networks	6
Summing networks	20
Inverter networks	12
Multipliers	8

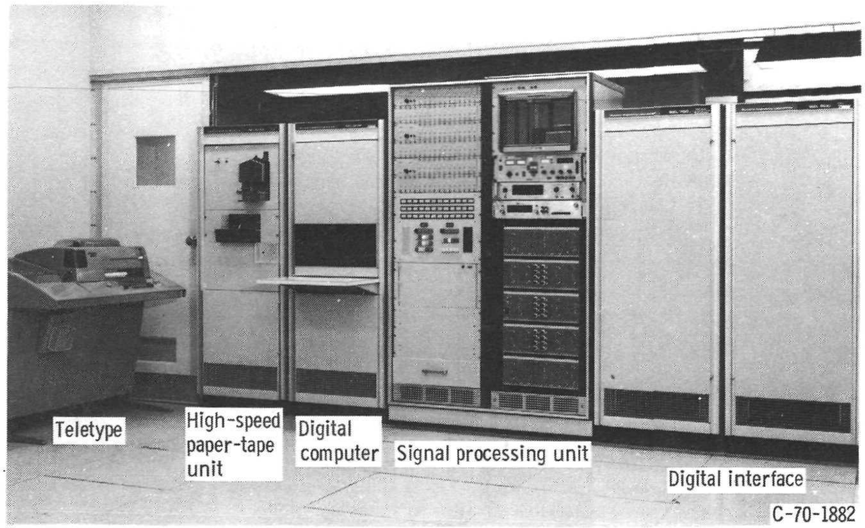

Figure 1. - Digital control system.

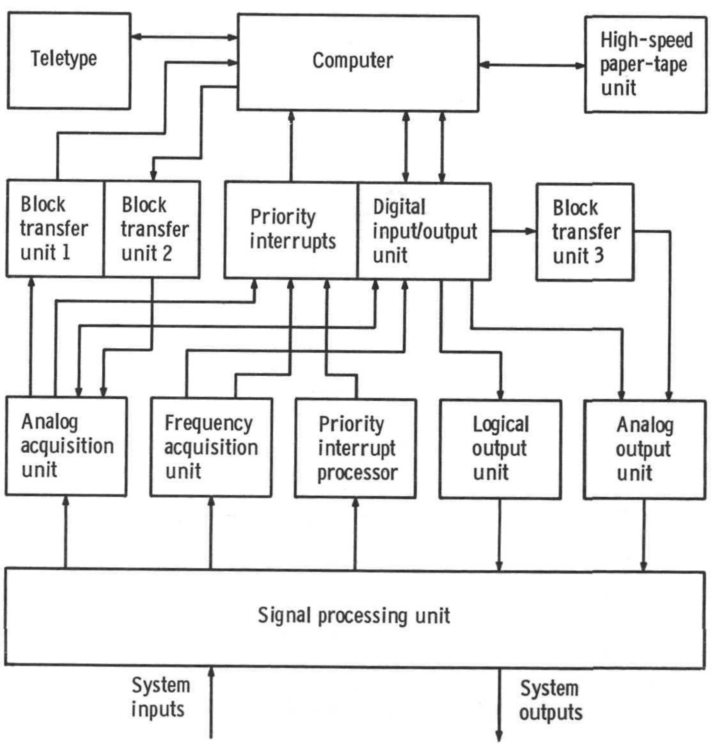

Figure 2. - Digital control system.

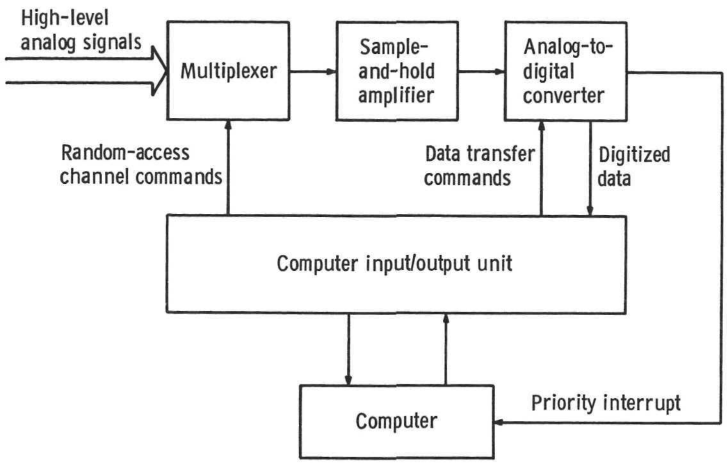

Figure 3. - Analog acquisition unit.

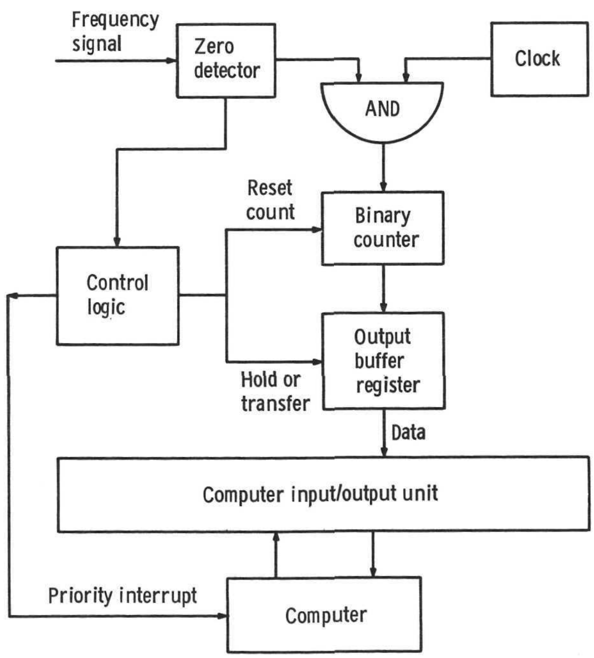

Figure 4. - Frequency acquisition unit.

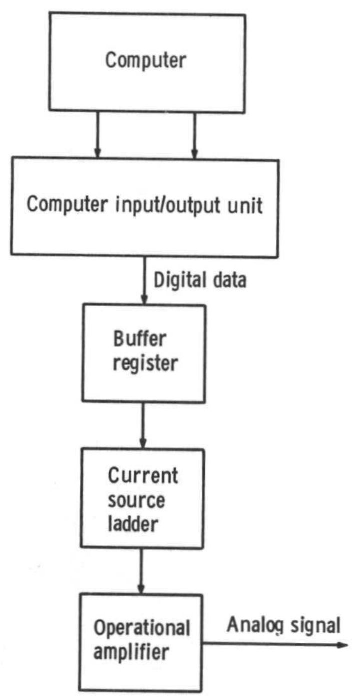

Figure 5. - Analog output unit.

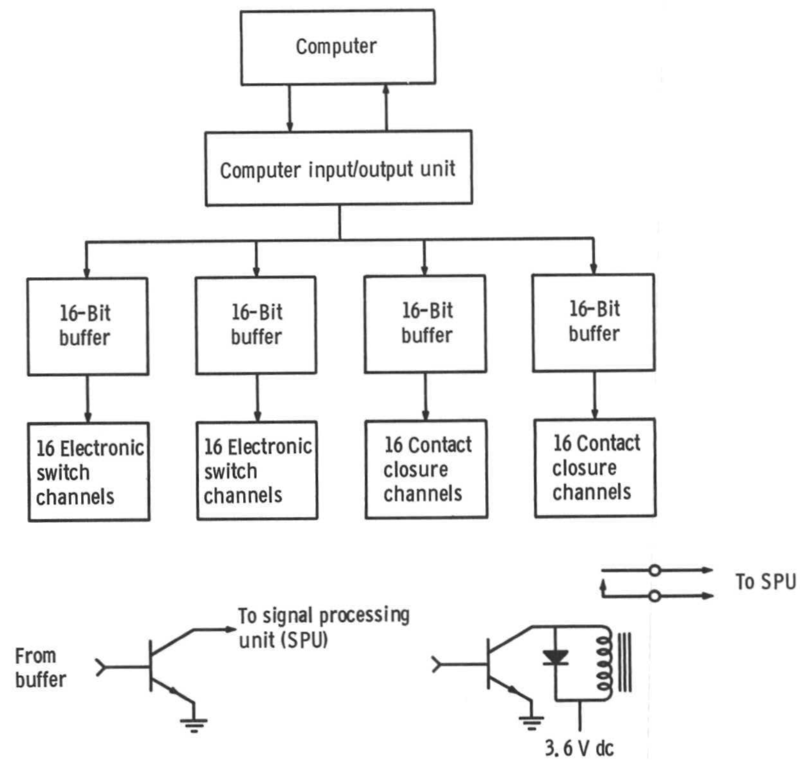

Figure 6. - Logical output unit.

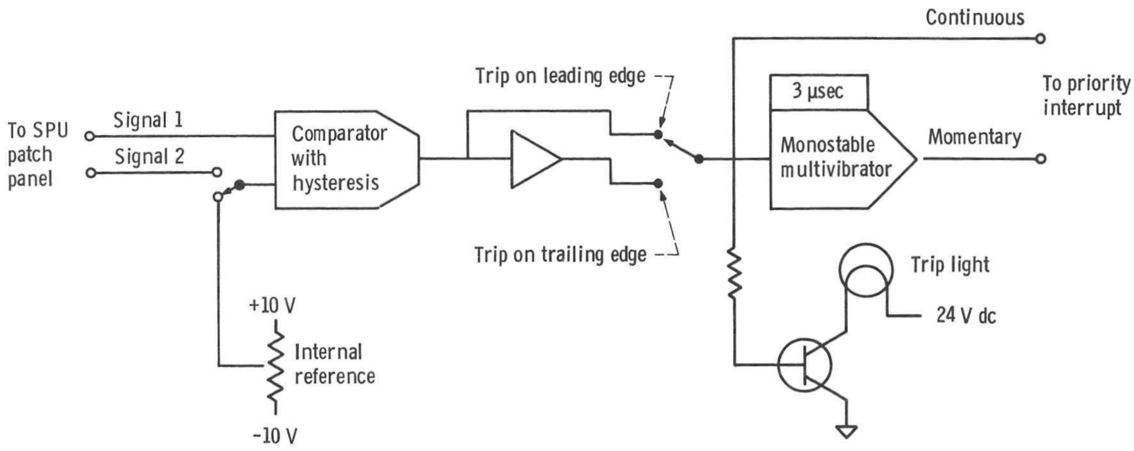

Figure 7. - Priority interrupt processor.

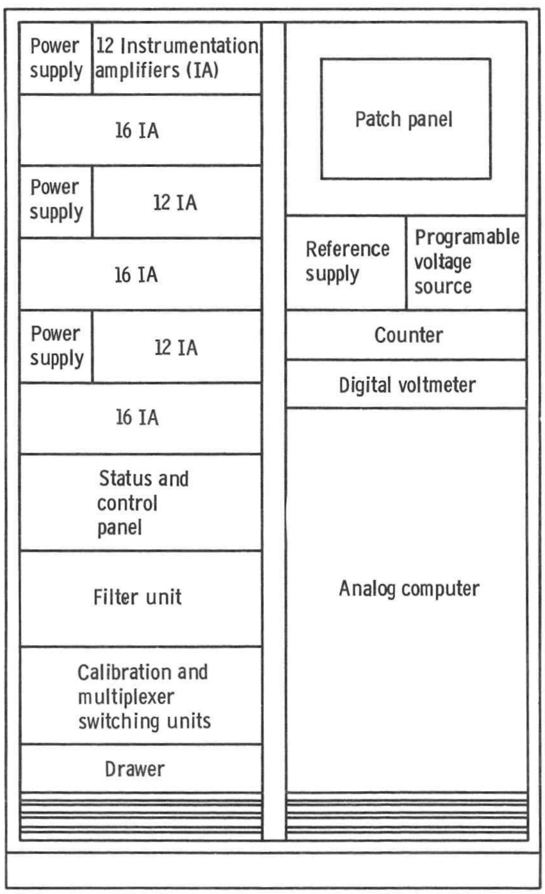

Figure 8. - Signal processing unit cabinet layout.

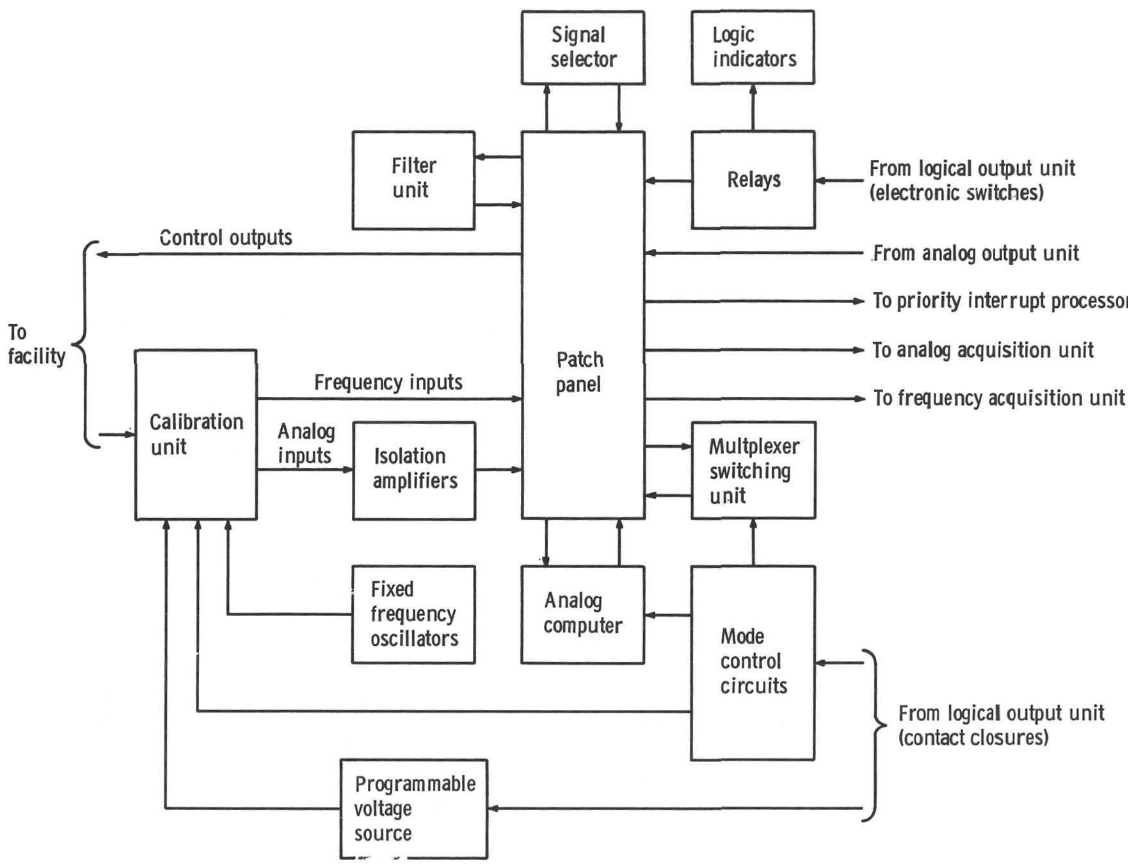

Figure 9. - Functional diagram of signal processing unit.

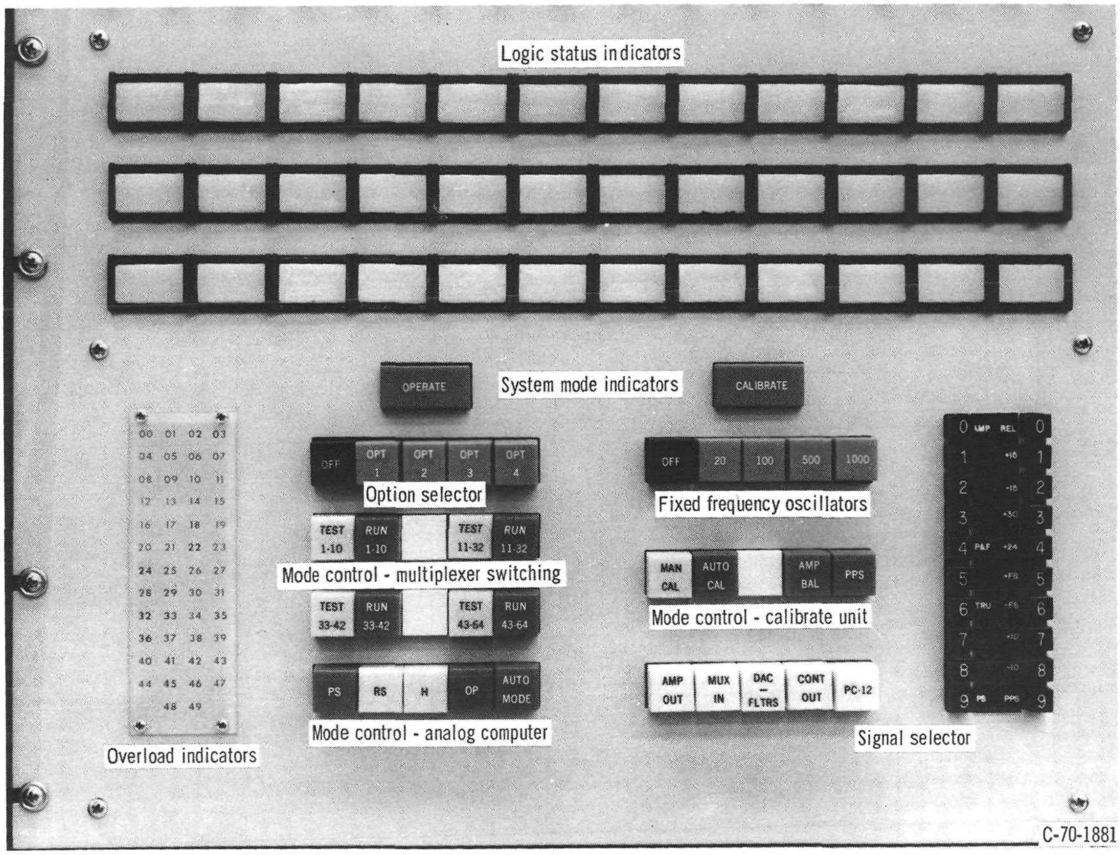

Figure 10. - Signal processing unit control panel.

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